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Title: An independent method for determining cascade efficiencies of the DANCE array

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Los Alamos
NATIONAL LABORATORY

An independent method for determining cascade efficiencies of the DANCE array

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Abstract: This report describes Monte Carlo simulations carried out to determine the detection efficiency of the Detector for Advanced Neutron Capture Experiments (DANCE) for γ-ray cascades following a neutron capture. This efficiency depends on the cascade multiplicity and hence on the isotope under investigation and possibly even on the neutron energy. A method for determining the cascade efficiency independent from other information besides the ones gained during the experiment got developed and tested.

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1 Introduction

This report describes simulations carried out to develop a independent method of determining the efficiency of the DANCE (***D****etector for* ***A****dvanced* ***N****eutron* ***C****apture* ***E****xperiments*) array for capture events (Figure 1 and Figure 2). The DANCE array is a 159-element 4π barium fluoride array designed to study neutron capture on small quantities of, potentially, radioactive material. It is located on a 20 meter neutron flight path (FP14), which views an "upper tier" water moderator at the Manuel J. Lujan Jr. Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE).

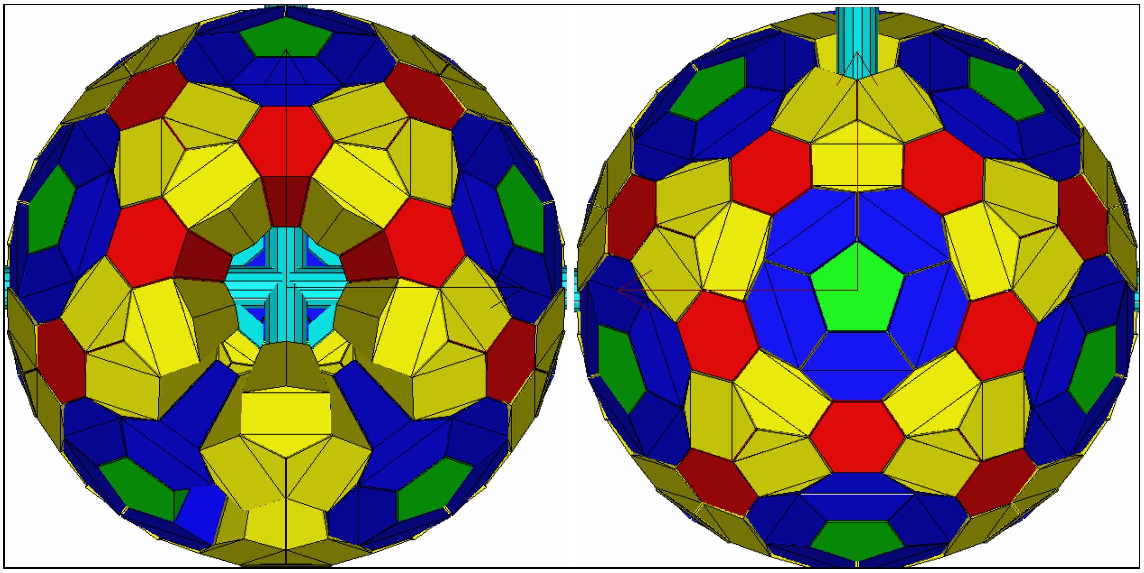

Figure 1: Views of the simulated setup: from right / left (relative to beam direction). Each color corresponds to a different crystal type (A – green, B – dark blue, C – yellow, D - red). The missing crystals allowing the beam pipe (light blue) to be seen were either not connected or not in place during the runs carried out during the commissioning phase 2002/2003.

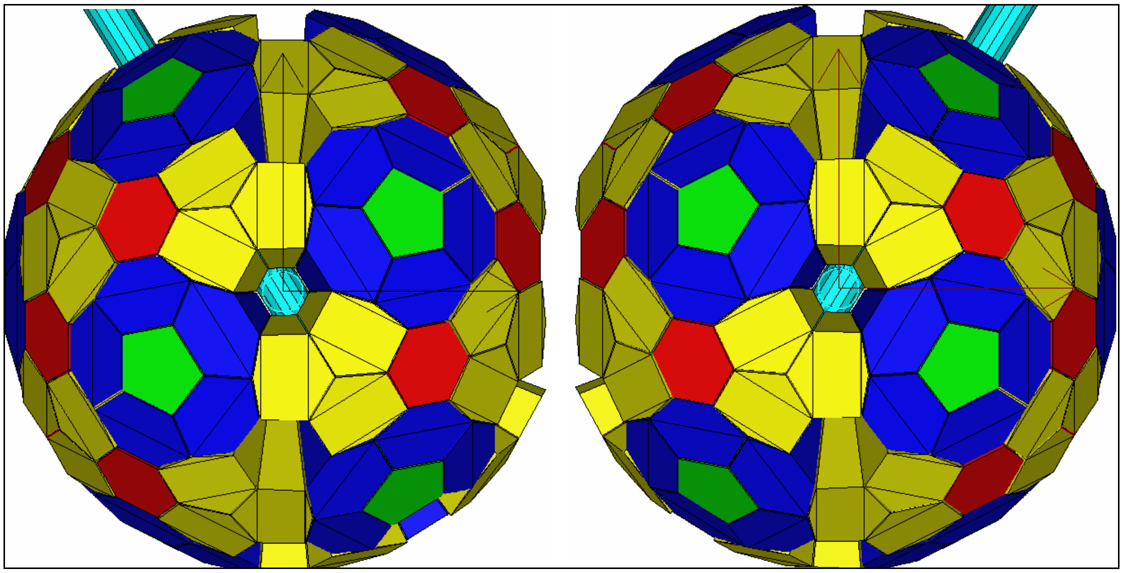

Figure 2: Views of the simulated setup: from downstream / upstream (relative to beam direction). Each color corresponds to a different crystal type (A – green, B – dark blue, C – yellow, D - red). The missing crystals allowing the beam pipe (light blue) to be seen were either not connected or not in place during the runs carried out during the commissioning phase 2002/2003.

The idea of using a 4π detector for detecting neutron capture events is based on the fact, that the total energy released as γ-rays after the actual reaction (Q-value) depends on the isotope. If the detector has an efficiency of 100%, all the emitted photons will deposit their energy in the scintillator and neutron captures on different isotopes will appear as counts in different channels of the energy spectrum. Therefore captures of neutrons, which got scattered at the sample, on the surrounding material, can be disentangled from captures on the sample simply by using the energy information. Captures of scattered neutrons are usually the dominant background component of neutron capture experiment, since this component scales with the sample mass and the scattering cross sections in the keV-region are very often 1 to 3 orders of magnitude bigger than the capture cross section. Efficient discrimination methods are therefore necessary for successful experiments.

The DANCE detector is designed as a so called 4π detector, but because of practical reasons the detector modules do not really cover the entire solid angle. Two crystals out of the 162 crystals, which would be necessary for a 4π array [1] are needed to be left out in order to leave space for a neutron beam pipe. Depending on the experiment, one crystal can be replaced by a sample changer mechanism, allowing to remotely exchange up to 3 samples without closing the beam shutter and breaking the vacuum of the beam pipe. This means, the full array is designed to host 159 or 160 out of 162 possible BaF_2 crystals. Furthermore the crystals can not be packed infinitely tide. The gap between the crystals reduces the effective solid angle covered. Last not least the intrinsic efficiency of a 15 cm BaF_2 crystal is not 100%. Even with a 4π coverage of the solid angle, a few of the emitted photons would not be detected. All together the total efficiency for a γ-ray of 1 MeV will be about 90%. Depending on the actual configuration the peak efficiency of typical capture cascades will be about 60%.

Depending on the signal to background ratio, a smaller or bigger part of the spectrum can be analyzed for capture events. If the background is very high, it might only be possible to analyze capture events in a small energy window around the Q-value. In contrast to the total efficiency, the peak efficiency depends strongly on the type of cascades emitted by the nucleus. If the average multiplicity is high and the emitted photons have small energies, the peak efficiency will be significantly smaller than for cascades with lower multiplicity and higher energetic photons. If there are no information available about the neutron capture cascades of the sample under investigation, a method needs to be found, which allows to reproduce the shape of the energy spectrum in the DANCE array.

This report is focused on simulations carried out in order to find and test such a method. It will turn out, that especially for the full array running – and not only 141 crystals like during the first commissioning phase (2002/2003) – promising attempts were found.

2 Gold cascades

In order to illustrate the effect of using different cascades, theoretically two sets derived as well as experimentally based cascades have been simulated. All are related to neutron capture on ^{197}Au. Since the DANCE array has been used in 4 different setups, each simulation has been carried out for using the following 4 sets of parameters:

- 141 crystals, high threshold, without ^{6}LiH absorber. This was the first setup of the DANCE array. Not all the crystals had been delivered yet and the ^{6}LiH absorber shell, which is used to reduce the number of scattered neutrons on their way from the sample to the BaF_2 crystals, was not installed. The results of these simulation can be found in chapter 3.1.
- 141 crystals, high threshold, with ^{6}LiH absorber. The ^{6}LiH absorber, a shell of 11.5 cm inner radius and 16.5 cm outer radius was not installed inside the crystal ball. The results of these simulation can be found in chapter 3.2.

- 159 crystals, low threshold, without ^{6}LiH absorber. During the shutdown phase in spring 2003 several improvements on the DANCE array have been made. As far as the simulation are concerned, the important changes were an increased number of crystals – the array got fully loaded with 159 crystals - and a decreased energy threshold on a single detector. Previous simulations have shown, that the peak efficiency of the array depends strongly this threshold [2]. The first experiments have been carried out without the ^{6}LiH absorber. The results of these simulation can be found in chapter 4.1.
- 159 crystals, low threshold, with ^{6}LiH absorber. This setup is likely to be close to the standard for all the experiments carried out with DANCE. The results are in chapter 4.2.

For more details on the simulated setups see Ref. [2]. The next chapters contain more information on the cascades used during the simulations.

2.1 keV-cascades without electron conversion

The first set of cascades was calculated by Uhl et. al. [3, 4]. The underlying model contains realistic assumptions about the deexcitation of the product nucleus ^{198}Au after radiative capturing of a 100 keV neutron. The model does not include the effect of electron conversion. This effect, where the energy is not released as a γ-ray, but as an accelerated electron out of the lower atomic electron shells, is especially important, if an isotope with a high proton number and low-energy transitions are involved.

2.2 keV-cascades with electron conversion

In contrast to the cascades discussed above Becvar et. al [5, 6] takes the effect of the electron conversion into account. The neutron energy range is the same as for the cascades without conversion, but the underlying nuclear model is different. Realistic simulations of (n,γ) including emitted electrons as well as γ-rays are therefore possible. The theoretical cascades are shown to agree with the experimental data within a few percent [7].

2.3 Thermal neutron capture database

Information on thermal neutron capture is available for most of the stable nuclei (see e.g. [8]). The data are usually not available as cascades, but as yield spectra. This means the averaged number of γ-rays of a certain energy per decay is documented, but not the information about which of them are emitted coincident. For the purpose of this report a program has been developed, which creates cascades based only on the yield information.
As it will turn out, the results obtained after the actual simulation of those cascades are not satisfying. The biggest problem is the lack of data, when no single γ-lines can be resolved, because the level density in the product nucleus is too high. Therefore no further details will be given about this attempt.

2.4 DANCE

Since DANCE is a 4π array, able to detect all the photons out of a single cascade with a high probability a natural and much more general attempt of gaining information about the underlying cascades, is to use the information acquired during the actual experiment. Assuming that only a small region around the Q-value of the reaction contains a negligible background, a reliable

method for reconstructing the cascade information and hence the peak efficiency of the DANCE array needed to be developed and tested.
The following two methods for reconstructing primary cascade information have been investigated:

1. Cascades were simulated on a event by event basis.
2. If the energy, deposited in the detector, was within 200 keV of the Q-value ($\left|Q - E_{cascade}\right| \le 0.2\,\mathrm{MeV}$), the event was further processed.
3. Single γ-ray energies were extracted based on:
   a. the energy information per single crystal.
   b. the energy information per cluster of crystals, where a number of crystals are called a cluster, if they are adjacent. The energies of all the crystals within one cluster are summed together.
4. In order to correct for the energy spread, the cascades were tuned to be all of the same energy:
   a. If $E_{cascade} > Q$: $E_\gamma^{'} = E_\gamma^{'} \cdot {}^{Q}\!/_{E_{cascade}}$
   b. If $E_{cascade} < Q$: $E_\gamma^{'}\left(multiplicity\right) = E_\gamma^{'}\left(multiplicity\right) + Q - E_{cascade}$

The Q-value for all the gold simulations was 6.613 MeV, which corresponds to a capture of a neutron with 100 keV energy.

The following procedure has been carried out in order to test the cascade reconstruction method:

1. Primary cascades of different averaged multiplicities and Q-values have been simulated for the four different setups, see section 2.
2. Secondary cascades were reconstructed as described above.
3. The secondary cascades were simulated. The number of simulations of each cascade was depending on their actual peak efficiency. Each cascade got repeatedly simulated, with different emission angles, until 10 counts originating from this cascade appeared in the energy window $\left|Q - E_{cascade}\right| \le 0.2\,\mathrm{MeV}$. This ensures that cascades with a low peak efficiency are weighted in the same way as cascades with a high peak efficiency.
4. The resulting spectra of the to sets of simulations have been compared.

3 141 crystals & high threshold

The motivation for the simulations carried out in this chapter was to illustrate the problem of choosing the "right" set of cascades. Since the setup of 141 crystals and high threshold was only used for a short time, not all cascades have been simulated with this setup.

3.1 Without ^{6}LiH absorber

Figure 3 shows the results for the setup 141 crystals, high threshold and no ^{6}LiH absorber for the cascades described in chapters 2.1, 2.2, and 2.3. The differences between the different cascades are remarkable. On the right part of Figure 3, the impact of the different curves might become more clear, because the y-axis corresponds to the efficiency above a certain total energy threshold, or in other words the cascade efficiency.

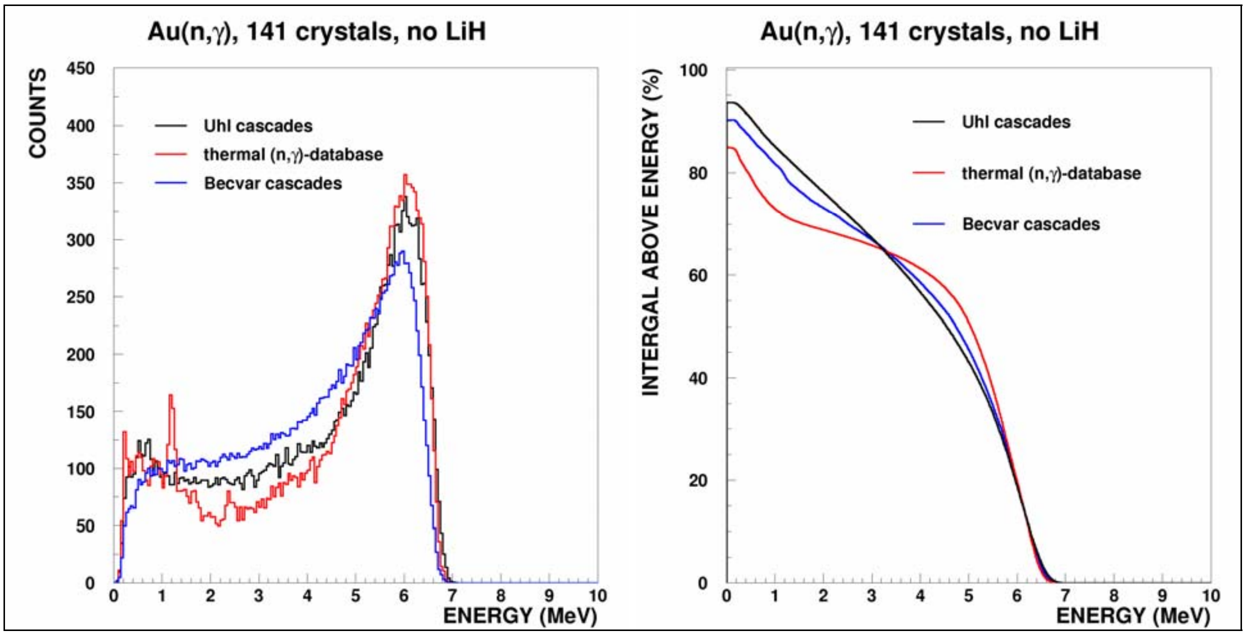

Figure 3: Left: Simulated response of the DANCE array with 141 crystals and high detector threshold to different gold cascades. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

Figure 4 shows the results of simulations, where the cascades have been reconstructed from simulations using the cascades created by Uhl et. al. If a correct method of reconstructing the cascades would exist, the original curve and the ones based on the reconstruction should be on top of each other. The two curves “DANCE cascades – single detector” and “DANCE cascades – single clusters” are the based on attempts described in the preceding section. Single detector means that the cascades where gained by assuming that one γ-ray deposits energy in one and only one detector. In reality however, the probability of depositing energy in ore than one detector for a mono-energetic γ-ray with energies around 1 MeV is about 25% [9]. This so called “cross talking” leads to a systematically overestimated cascade multiplicity, if no further correction are applied. This effect is taken into account in the curves called single cluster. Here the underlying assumption is, that a single γ-ray deposits energy only in neighboring detectors. Neighboring crystals with an energy deposition above the threshold are considered to be a single cluster and their energy depositions are added up. If the integration threshold is high, this attempt reproduces the original simulations better.

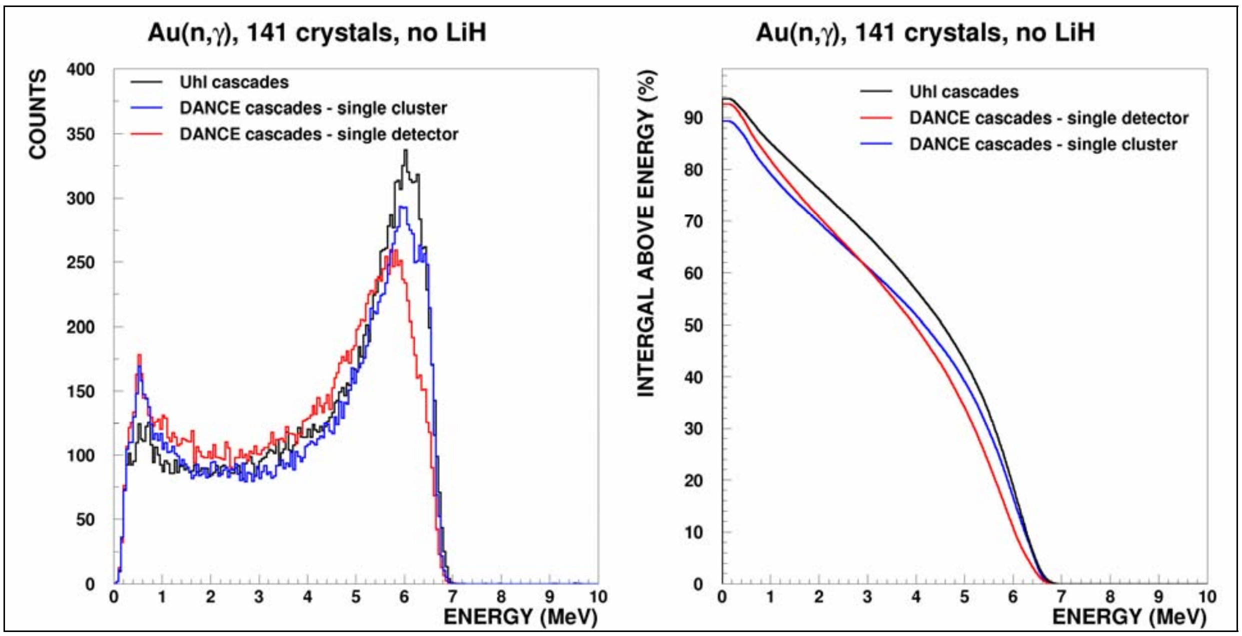

Figure 4: Left: Simulated response of the DANCE array with 141 crystals and high detector threshold to gold cascades gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

3.2 With ^{6}LiH absorber

Figure 5 and Figure 6 show the same results as in the preceding section, but including a ^{6}LiH absorber. While discrepancies between the different primary cascades remain (Figure 5), the reconstructing method works already remarkably well (Figure 6).

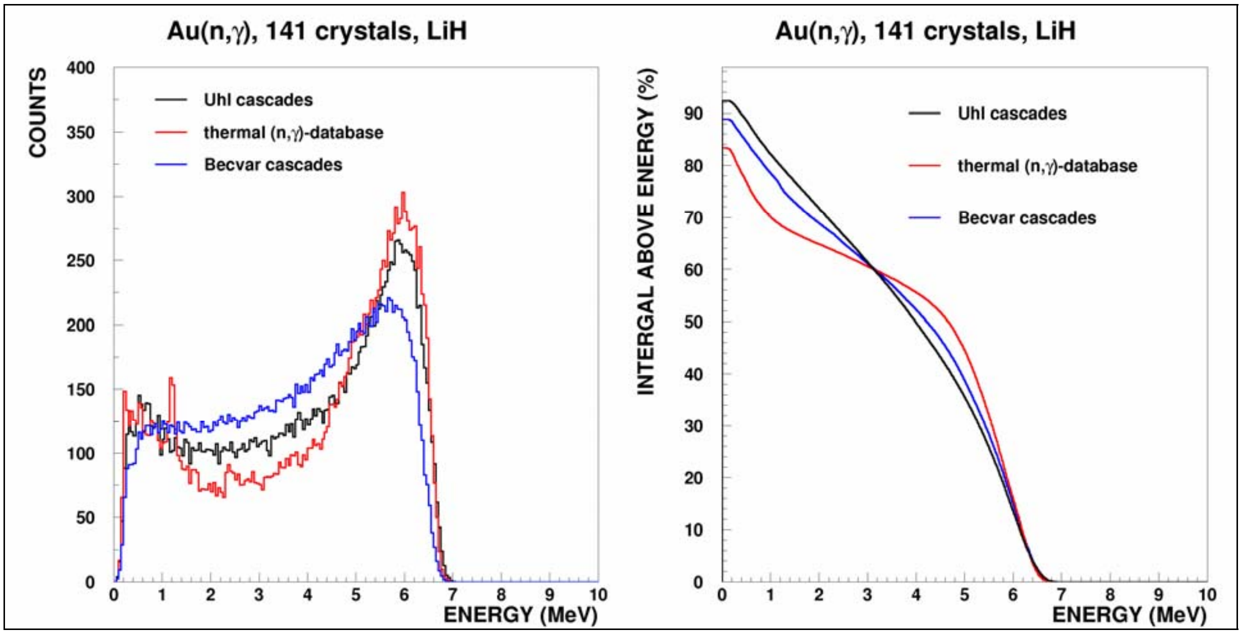

Figure 5: Left: Simulated response of the DANCE array with 141 crystals and high detector threshold to different gold cascades. A LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

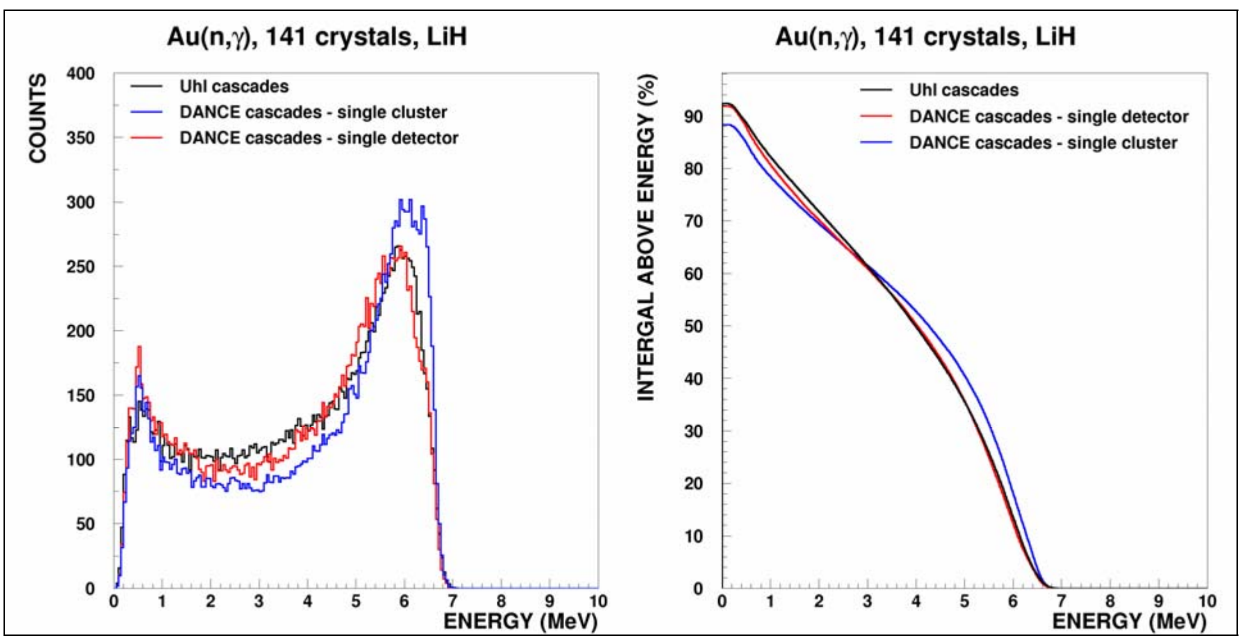

Figure 6: Left: Simulated response of the DANCE array with 141 crystals and high detector threshold to gold cascades gained from the preceding simulation. A LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

4 159 crystals & low threshold

4.1 Without ^{6}LiH absorber

Figure 7 shows the results for the setup 159 crystals, low threshold and no ^{6}LiH absorber for the cascades described in chapters 2.1, 2.2, and 2.3. The differences between the different primary cascades remain, even for the almost 4π array with optimized single detector thresholds. The right part of Figure 7, shows again the integrated version. As in the case with 141 crystals and high detector threshold (Figure 3), the different shapes resulting from different primary cascades are still not satisfying.

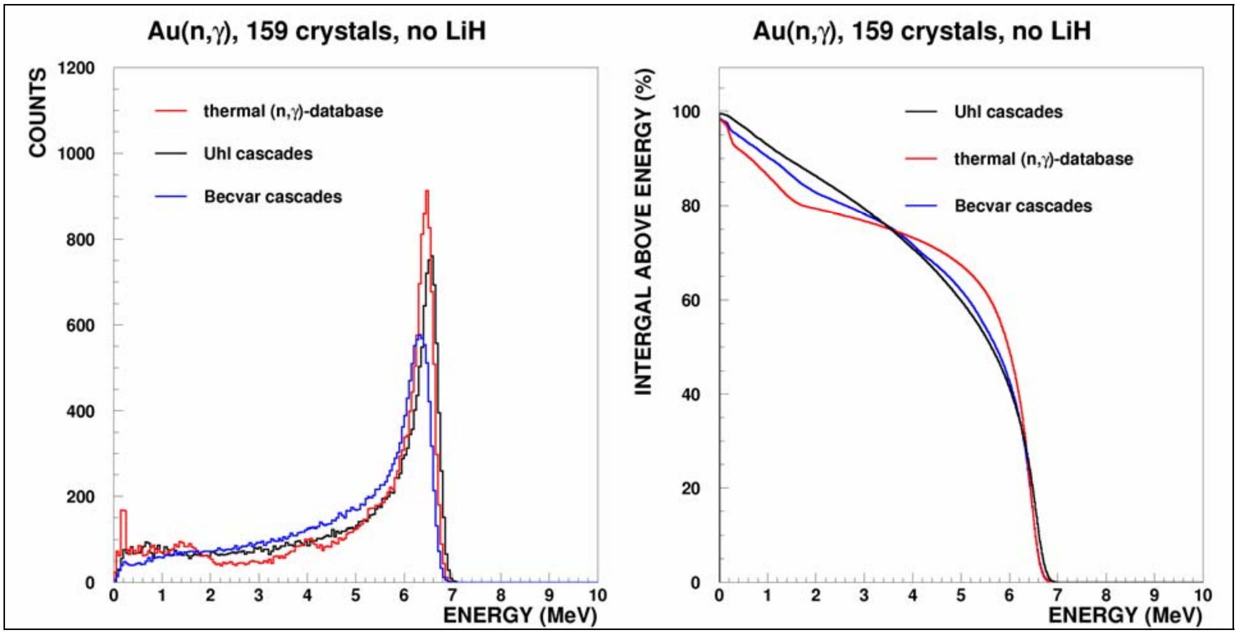

Figure 7: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to different gold cascades. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

Quite in contrary are the results gained with the cascade reconstruction method. Figure 8 shows an remarkable agreement between the reconstructions gained using cluster information. As a comparison also the results using the single crystal information are plotted, which works obviously worse. Since the details can not be seen in Figure 8, more information of the region of interest (Figure 9) as well as a quantitative comparison of the original cascade simulation and the reconstructed information, called 'DANCE cascades' (Table 1) can be found below. The blue lines Table 1 correspond to the most interesting region. If it would be necessary to set a cut on the total energy deposited in the crystal ball, those are the likely values, since the signal to background ratio is highest close to the Q-value (6.613 MeV in this case) of the reaction of interest. If the integration interval used to analyze the number of counts from the ^{197}Au(n,γ) reaction starts at 6 MeV or lower, the efficiency of the DANCE array can be reproduced with a relative uncertainty of less than 3%.

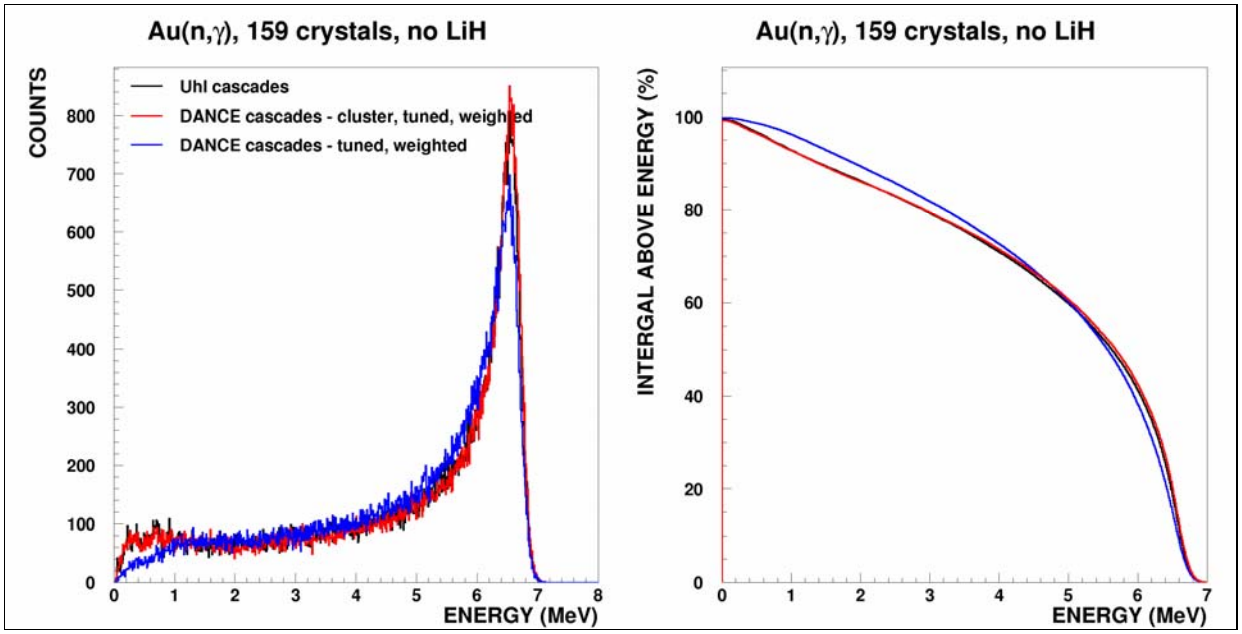

Figure 8: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to gold cascades gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

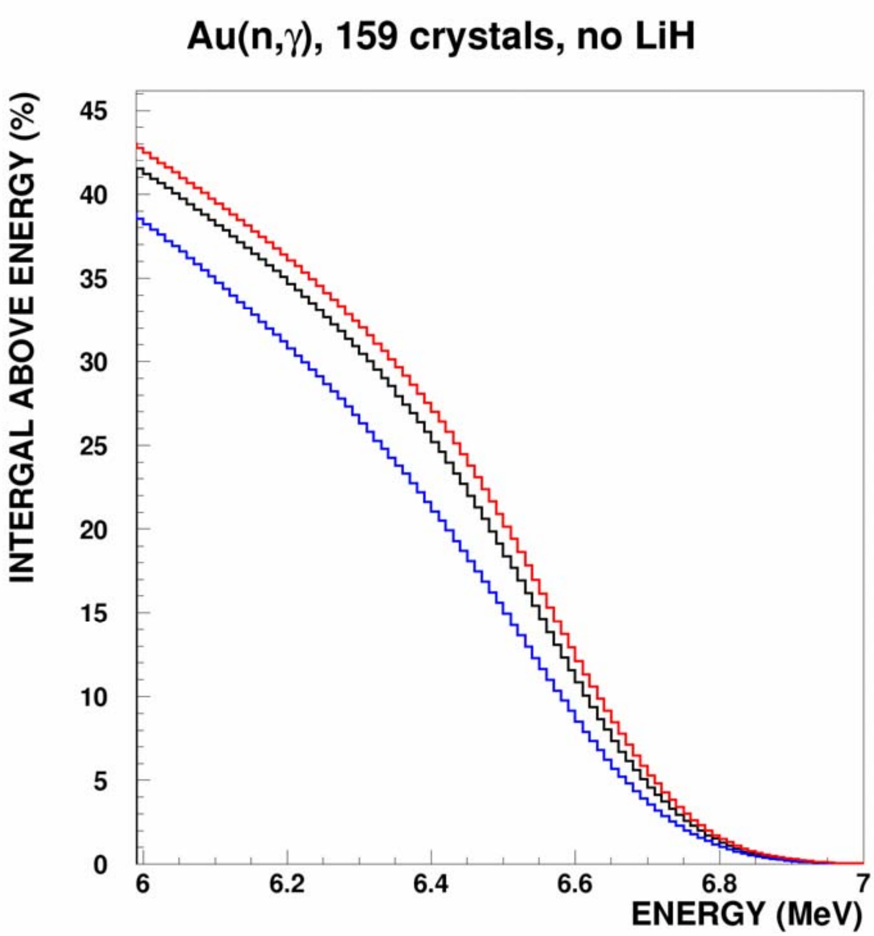

Figure 9: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 8.

Table 1: The first 3 columns contain the same data as the right part of Figure 8. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Uhl	Efficiency (%) Cluster	Rel. Difference (%)
0	99.5	99.3	**0.3**
0.2	99.0	98.7	**0.3**
0.4	97.5	97.2	**0.3**
0.6	96.1	95.8	**0.3**
0.8	94.4	94.3	**0.1**
1	92.9	92.8	**0.1**
1.2	91.5	91.4	**0.1**
1.4	90.1	90.0	**0.1**
1.6	88.8	88.6	**0.2**
1.8	87.5	87.3	**0.3**
2	86.3	86.1	**0.2**
2.2	85.0	84.9	**0.0**
2.4	83.6	83.7	**0.0**
2.6	82.2	82.3	**-0.1**
2.8	80.8	80.9	**-0.1**
3	79.3	79.5	**-0.2**
3.2	77.8	78.0	**-0.2**
3.4	76.3	76.5	**-0.3**
3.6	74.6	74.9	**-0.5**
3.8	72.8	73.3	**-0.7**
4	71.0	71.5	**-0.8**
4.2	69.1	69.6	**-0.8**
4.4	67.0	67.6	**-0.9**
4.6	64.8	65.5	**-1.2**
4.8	62.4	63.3	**-1.3**
5	59.9	60.7	**-1.3**
5.2	57.1	58.0	**-1.5**
5.4	54.2	55.0	**-1.6**
5.6	50.6	51.7	**-2.1**
5.8	46.6	47.7	**-2.4**
6	41.5	42.7	**-2.9**
6.2	35.1	36.4	**-3.7**
6.4	25.8	27.5	**-6.5**
6.6	11.6	12.9	**-11.0**
6.8	1.5	1.7	**-12.7**
7	0.0	0.0	**0.0**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

Having agreement described above in mind, in needed to be tested, if this is only the case for the primary cascades by Uhl et. al. [3, 4] with an average cascade multiplicity of 3.61, or if this method really works as independent as it was intended. The purpose of the next simulations was to investigate this quest. Figure 10 shows the result of the same simulations as above, but the primary cascades consisted only of a single cascade with one single γ-ray of 6.613 MeV. In other words, the simulations have been carried out under the extreme assumption that after each neutron capture the entire energy is emitted in one single gamma.

Figure 11 and Table 2 contain again more detailed information. The agreement between the simulations of the primary cascade and the secondary DANCE cascades using the cluster algorithm is even slightly better than for the cascades by Uhl.

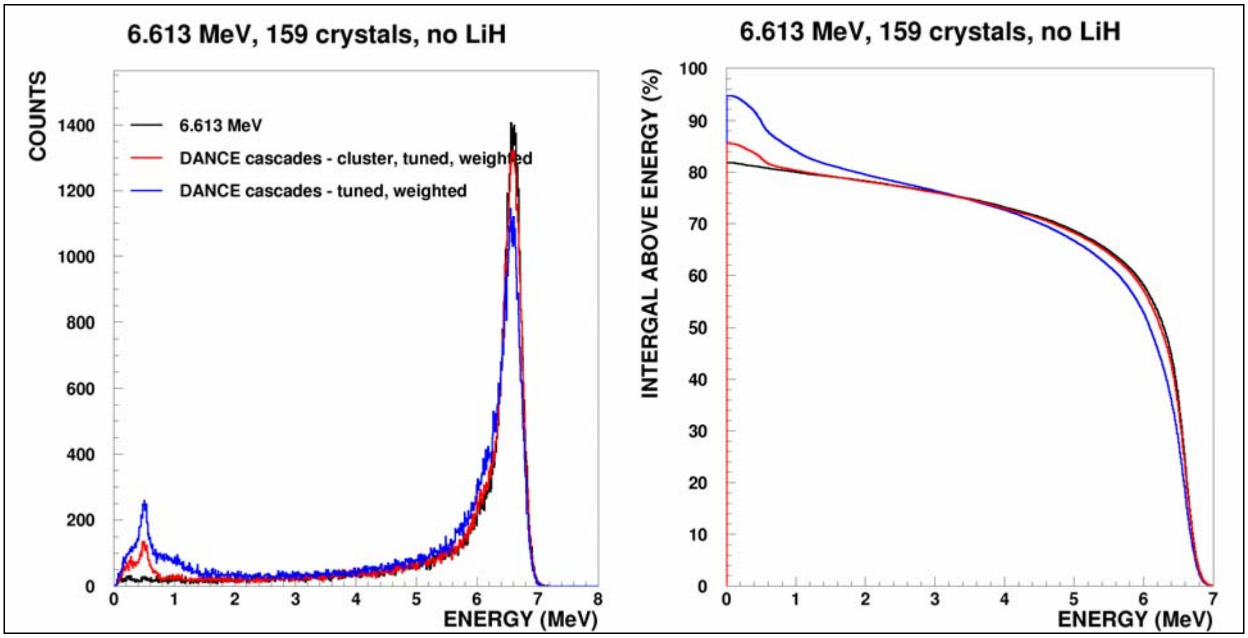

Figure 10: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to a single 6.613 MeV γ-ray gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

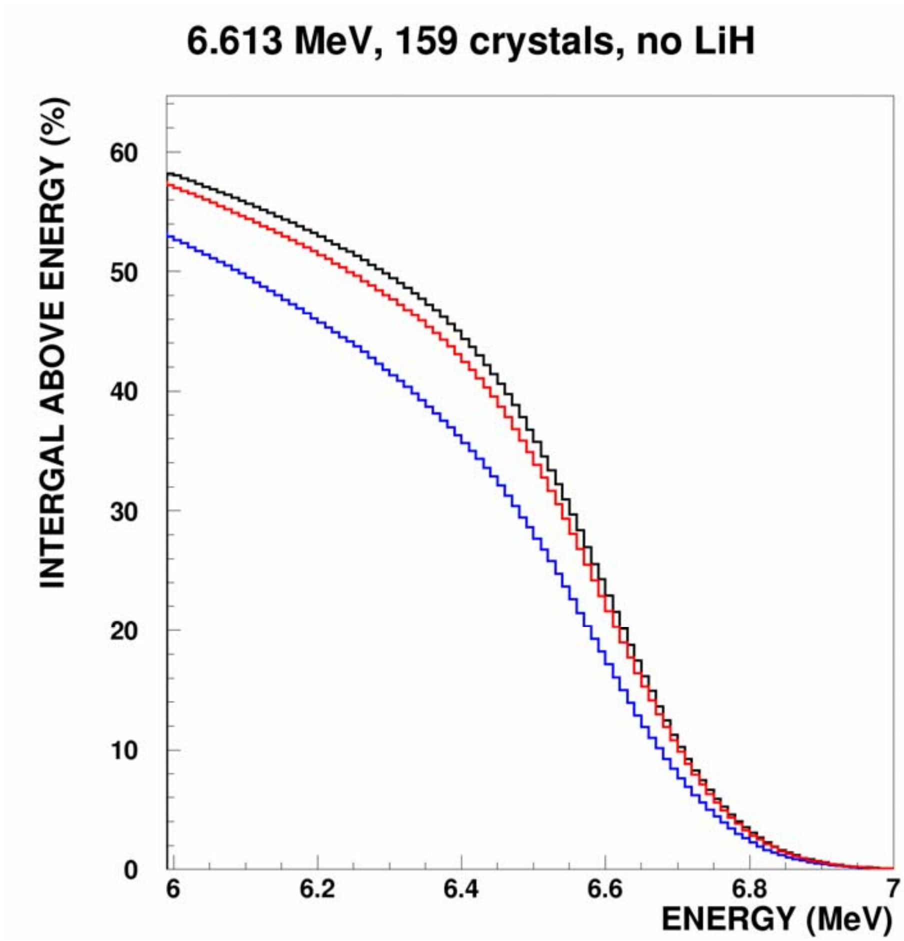

Figure 11: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 10.

Table 2: The first 3 columns contain the same data as the right part of Figure 10. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Primary	Efficiency (%) Cluster	Rel. Difference (%)
0	81.9	85.6	**-4.4**
0.2	81.6	85.1	**-4.1**
0.4	81.2	83.7	**-3.1**
0.6	80.8	81.7	**-1.1**
0.8	80.4	80.9	**-0.6**
1	80.0	80.4	**-0.4**
1.2	79.6	79.9	**-0.3**
1.4	79.3	79.5	**-0.2**
1.6	79.0	79.0	**0.0**
1.8	78.7	78.6	**0.1**
2	78.3	78.2	**0.1**
2.2	77.9	77.8	**0.1**
2.4	77.5	77.4	**0.1**
2.6	77.1	77.0	**0.1**
2.8	76.6	76.5	**0.1**
3	76.2	76.1	**0.1**
3.2	75.7	75.5	**0.2**
3.4	75.1	75.0	**0.2**
3.6	74.6	74.4	**0.3**
3.8	73.9	73.7	**0.3**
4	73.2	72.9	**0.4**
4.2	72.5	72.2	**0.4**
4.4	71.7	71.4	**0.4**
4.6	70.9	70.5	**0.5**
4.8	69.8	69.4	**0.5**
5	68.6	68.2	**0.6**
5.2	67.2	66.8	**0.6**
5.4	65.6	65.2	**0.7**
5.6	63.7	63.2	**0.9**
5.8	61.3	60.7	**1.1**
6	58.0	57.0	**1.8**
6.2	52.9	51.4	**2.9**
6.4	44.3	42.4	**4.5**
6.6	22.9	21.6	**6.0**
6.8	3.1	2.8	**7.2**
7	0.1	0.1	**-3.5**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

The results second test of the independence from the primary cascades is shown in Figure 12. Instead of an average multiplicity of 1 or 3.61 the cascades were chosen to have a multiplicity of 9. The same cascade consisting of 9 γ-rays with energies of 2x 0.1, 2x 0.2, 2x 0.3, 0.4, 1.4 and 3.613 MeV was simulated for each event. Figure 13 and Table 3 show that even in this extreme case, were in each cascade two γ-rays have energies close to the single detector threshold of 50 keV, the agreement is better than 3% for lower integration limit of 6 MeV or below.

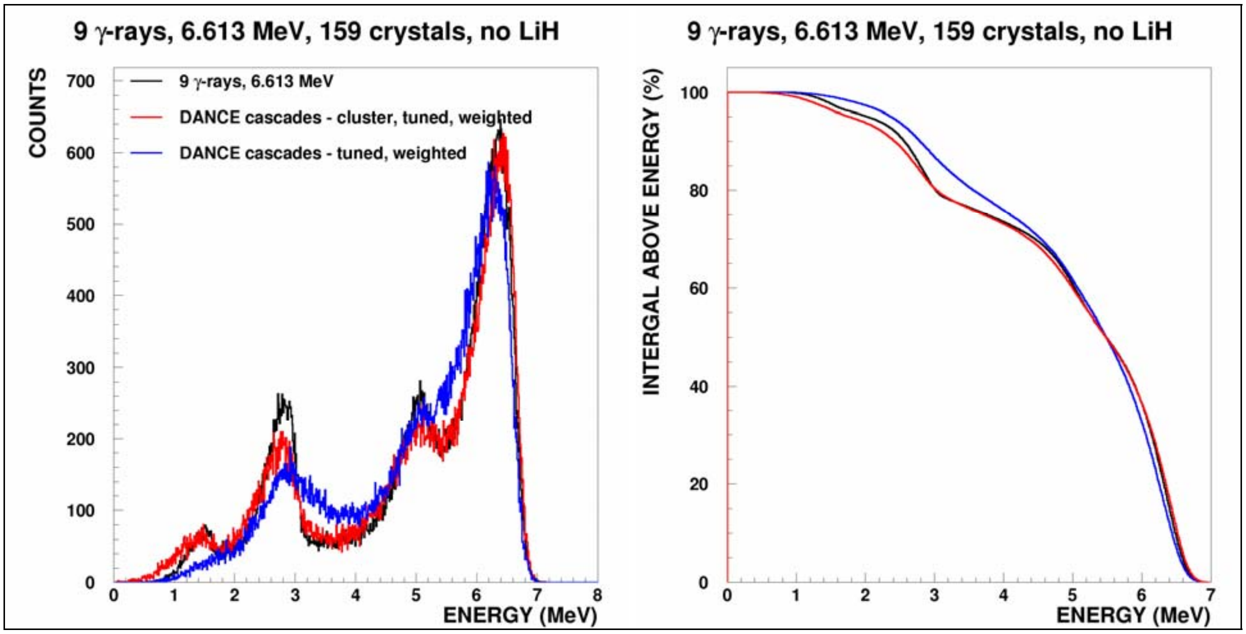

Figure 12: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to 9 γ-rays with energies of 2x 0.1, 2x 0.2, 2x 0.3, 0.4, 1.4 and 3.613 MeV (the sum is 6.613 keV) gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

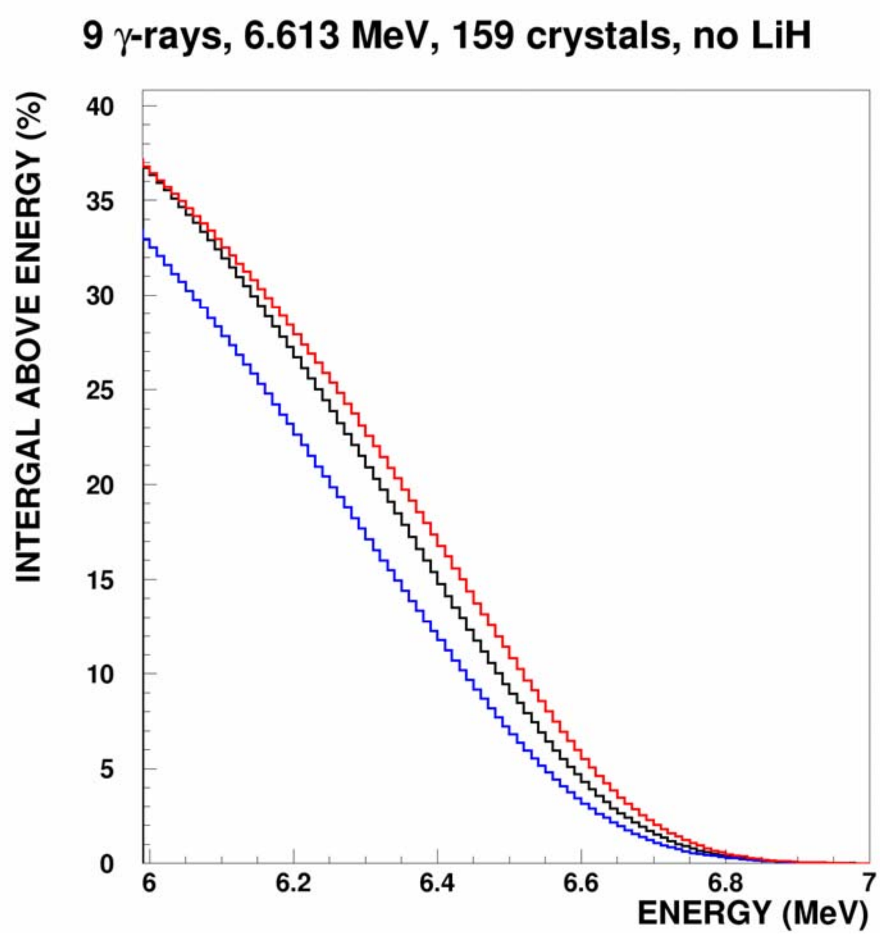

Figure 13: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 12.

Table 3: The first 3 columns contain the same data as the right part of Figure 12. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Primary	Efficiency (%) Cluster	Rel. Difference (%)
0	100.0	100.0	**0.0**
0.2	100.0	100.0	**0.0**
0.4	100.0	99.9	**0.1**
0.6	100.0	99.8	**0.2**
0.8	100.0	99.5	**0.4**
1	99.8	99.0	**0.8**
1.2	99.3	98.1	**1.2**
1.4	98.3	97.0	**1.3**
1.6	96.9	95.8	**1.2**
1.8	96.0	94.8	**1.3**
2	95.1	93.8	**1.4**
2.2	94.1	92.4	**1.8**
2.4	92.3	90.2	**2.3**
2.6	89.3	87.4	**2.2**
2.8	84.8	83.7	**1.3**
3	80.2	80.3	**-0.2**
3.2	78.1	78.3	**-0.2**
3.4	77.0	76.9	**0.2**
3.6	75.9	75.6	**0.3**
3.8	74.7	74.4	**0.4**
4	73.5	73.1	**0.6**
4.2	72.1	71.6	**0.7**
4.4	70.5	69.6	**1.2**
4.6	68.3	67.1	**1.7**
4.8	65.1	63.8	**2.0**
5	60.7	59.9	**1.3**
5.2	55.7	55.6	**0.1**
5.4	51.6	51.6	**0.0**
5.6	47.7	47.5	**0.3**
5.8	43.1	42.8	**0.6**
6	36.3	36.4	**-0.2**
6.2	26.7	27.9	**-4.3**
6.4	14.7	16.8	**-12.9**
6.6	4.3	5.5	**-24.5**
6.8	0.4	0.5	**-28.4**
7	0.0	0.0	**0.0**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

4.2 With ^{6}LiH absorber

This section is motivated by the fact that the majority of the experiments at DANCE will be carried out using a ^{6}LiH neutron absorber shell inside the DANCE array. This shell with an inner radius of 10.5 cm and an outer radius of 16.6 cm effectively reduces the number of scattered neutrons reaching the BaF_2 crystals. On the other hand it absorbs also some of the γ-rays emitted by the sample after a neutron capture. The full energy peak will therefore be somewhat broader and the peak efficiency will be reduced. [2, 9]. The results presented here show that the cascade reconstruction method works also in this case.
Figure 14 shows again the discrepancies due to different primary cascades, underlining the need for an independent method of determining the efficiency of the array.

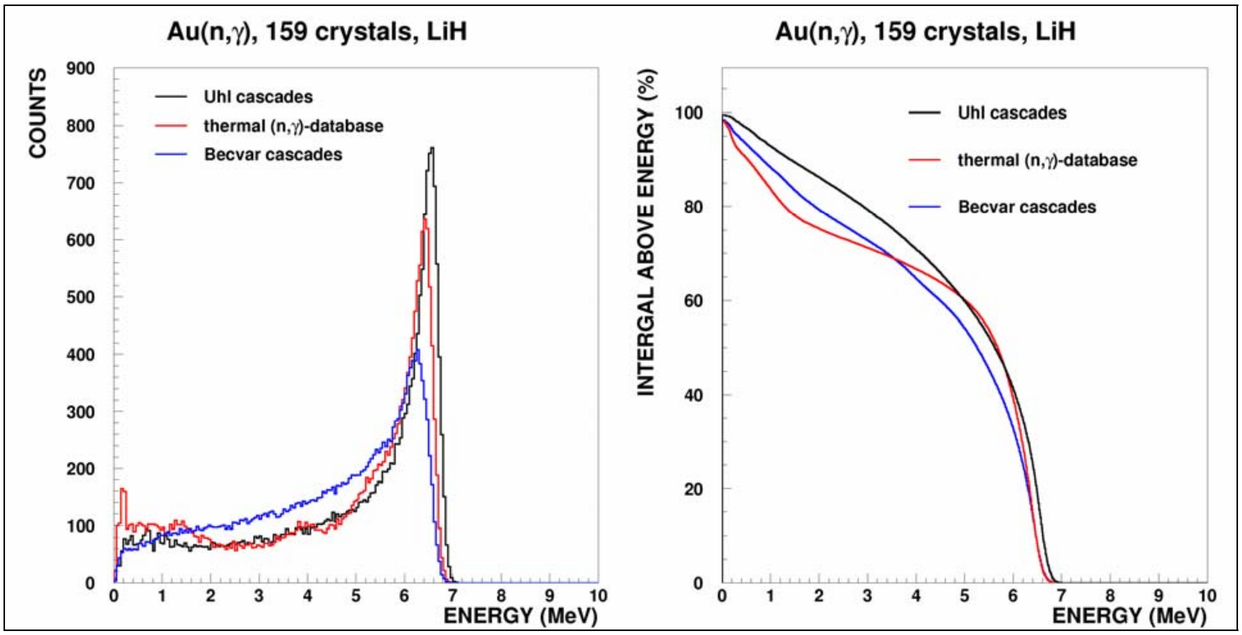

Figure 14: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to different gold cascades. A LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

Figure 15 shows the comparison of the simulations carried out with Uhl cascades as primary cascades, single detector based reconstructed cascades, and cascades based on cluster information. From Figure 16 and Table 4 one can conclude that the described reconstruction method works also with a ^{6}LiH neutron absorber included in the simulations.

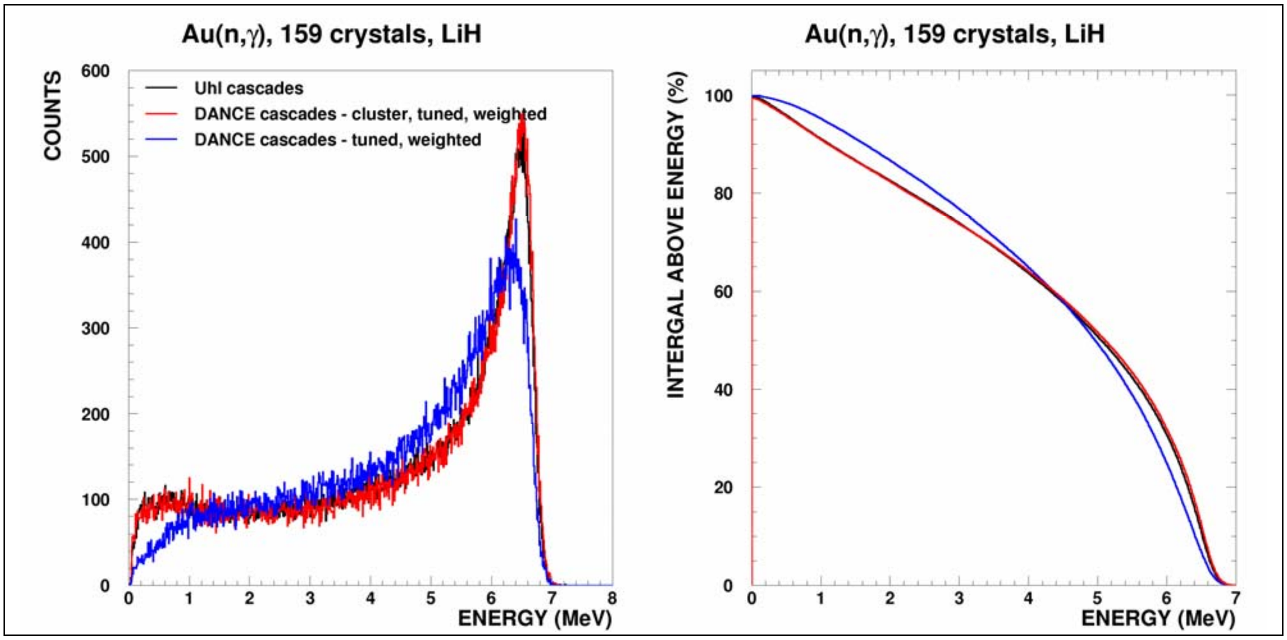

Figure 15: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to gold cascades gained from the preceding simulation. A LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

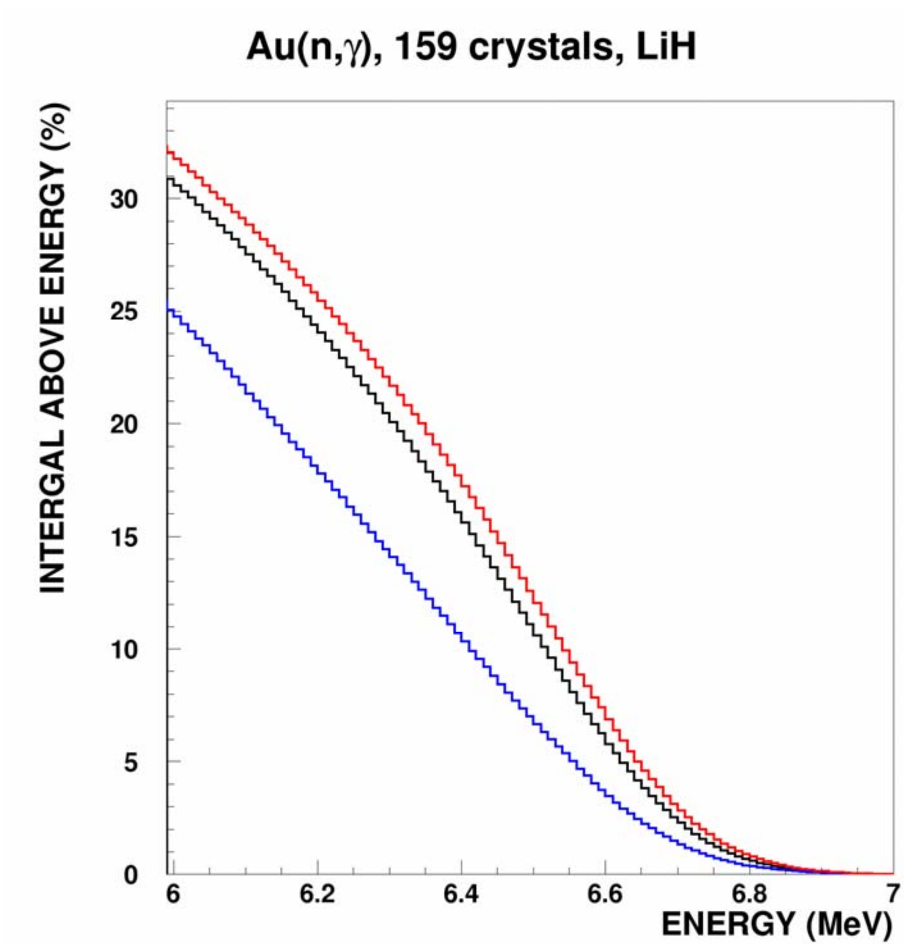

Figure 16: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 15.

Table 4: The first 3 columns contain the same data as the right part of Figure 15. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Uhl	Efficiency (%) Cluster	Rel. Difference (%)
0.0	99.6	99.3	**0.3**
0.2	98.6	98.2	**0.4**
0.4	96.7	96.5	**0.2**
0.6	94.9	94.7	**0.2**
0.8	92.9	92.8	**0.1**
1	91.0	90.9	**0.1**
1.2	89.2	89.1	**0.2**
1.4	87.5	87.4	**0.1**
1.6	85.8	85.7	**0.1**
1.8	84.2	84.0	**0.2**
2	82.5	82.3	**0.2**
2.2	80.8	80.5	**0.3**
2.4	79.1	78.9	**0.3**
2.6	77.4	77.1	**0.4**
2.8	75.7	75.4	**0.3**
3	73.8	73.7	**0.2**
3.2	72.0	72.0	**0.0**
3.4	70.0	70.2	**-0.2**
3.6	68.0	68.2	**-0.3**
3.8	65.9	66.2	**-0.4**
4	63.7	64.0	**-0.5**
4.2	61.4	61.8	**-0.7**
4.4	58.9	59.5	**-1.0**
4.6	56.4	57.1	**-1.1**
4.8	53.6	54.4	**-1.5**
5	50.7	51.5	**-1.6**
5.2	47.6	48.5	**-1.8**
5.4	44.2	45.2	**-2.2**
5.6	40.3	41.4	**-2.6**
5.8	35.9	37.1	**-3.1**
6	30.6	31.8	**-3.8**
6.2	24.0	25.5	**-5.8**
6.4	15.6	17.2	**-9.7**
6.6	5.8	6.9	**-17.2**
6.8	0.6	0.8	**-28.6**
7	0.0	0.0	**0.0**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

As in the case without a ^{6}LiH absorber it needed top be tested, if the cascade reconstruction gives good results, independent of the actual choice of the primary cascades. Therefore the simulations have been repeated with primary cascades of 1 (Figure 17). Figure 18 and Table 5 demonstrate the very good agreement in the region of interest.

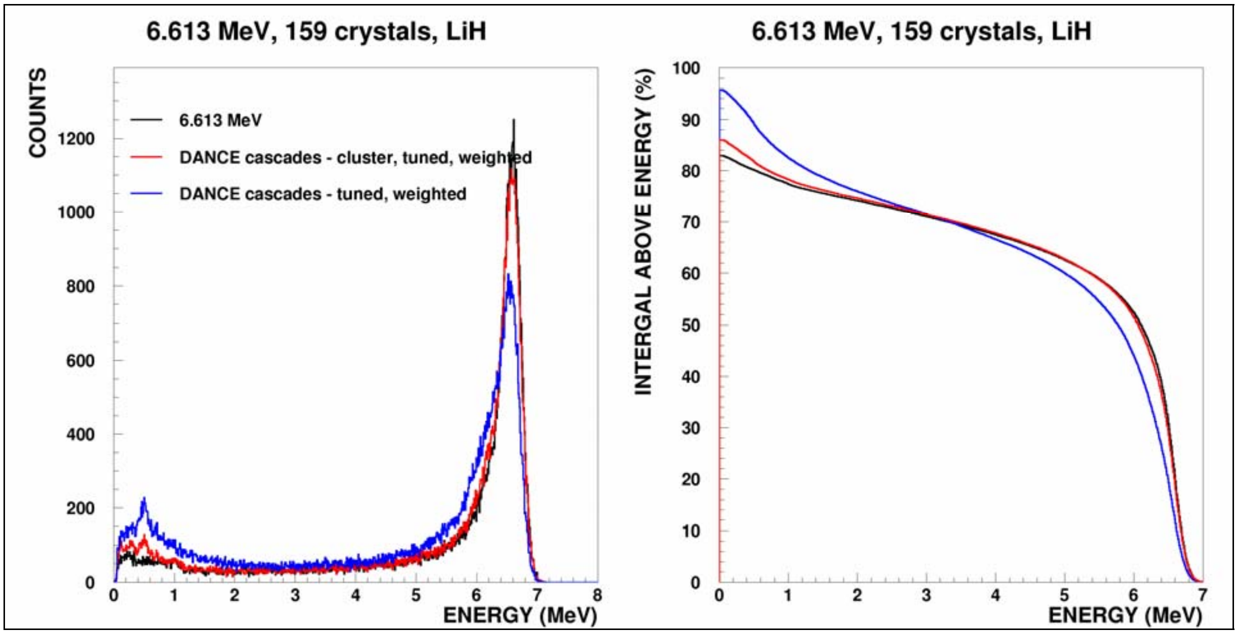

Figure 17: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to a 6.613 MeV γ-ray gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

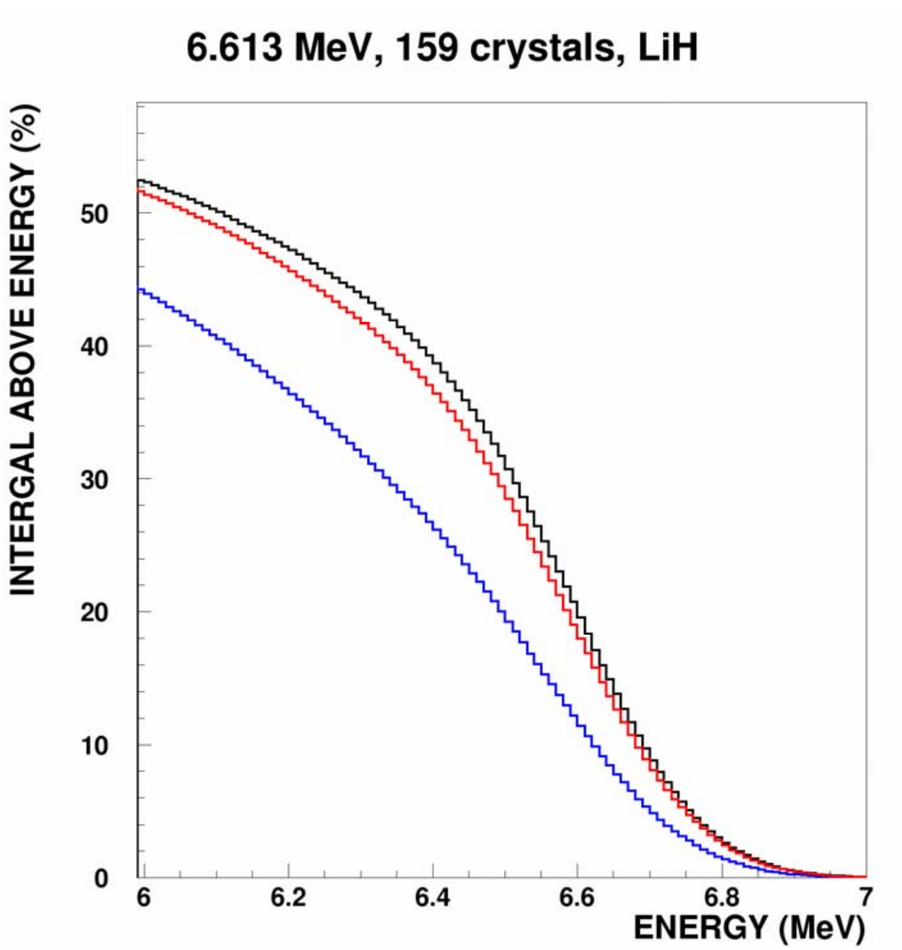

Figure 18: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 17.

Table 5: The first 3 columns contain the same data as the right part of Figure 17. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Primary	Efficiency (%) Cluster	Rel. Difference (%)
0	82.9	86.0	**-3.6**
0.2	82.0	84.7	**-3.3**
0.4	80.7	82.8	**-2.6**
0.6	79.6	80.8	**-1.6**
0.8	78.5	79.4	**-1.2**
1	77.4	78.3	**-1.1**
1.2	76.6	77.3	**-0.9**
1.4	75.9	76.5	**-0.8**
1.6	75.3	75.9	**-0.7**
1.8	74.7	75.2	**-0.6**
2	74.2	74.6	**-0.6**
2.2	73.5	74.0	**-0.7**
2.4	73.0	73.4	**-0.6**
2.6	72.3	72.8	**-0.6**
2.8	71.7	72.1	**-0.5**
3	71.1	71.4	**-0.5**
3.2	70.4	70.8	**-0.6**
3.4	69.7	70.1	**-0.5**
3.6	69.0	69.4	**-0.5**
3.8	68.3	68.6	**-0.5**
4	67.5	67.8	**-0.5**
4.2	66.7	66.9	**-0.4**
4.4	65.8	66.0	**-0.4**
4.6	64.8	65.1	**-0.3**
4.8	63.8	64.0	**-0.3**
5	62.6	62.7	**-0.3**
5.2	61.2	61.3	**-0.1**
5.4	59.8	59.6	**0.2**
5.6	57.9	57.7	**0.3**
5.8	55.5	55.1	**0.7**
6	52.3	51.4	**1.8**
6.2	47.2	45.6	**3.4**
6.4	38.7	36.4	**6.1**
6.6	19.6	18.0	**8.4**
6.8	2.6	2.4	**8.8**
7	0.0	0.0	**0.0**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

The last step of simulations confirmed that the described reconstruction method is in deed independent from the choice of primary cascades. Figure 19 shows the results of simulations including the ^{6}LiH absorber for primary cascades with multiplicity 9. Figure 20 and Table 6 contain more detailed information, which show that the agreement is slightly worse than for the previous cases. The reason is that γ-rays of only 100 keV a very likely to interact with the ^{6}LiH absorber or other material, leading to a potentially small energy loss. This means, even though the first step in reconstructing the cascades was accepting only cascades close to the Q-value, for some of the events analyzed only a part of the emitted γ-rays deposited all their energy in the BaF_2 crystals.

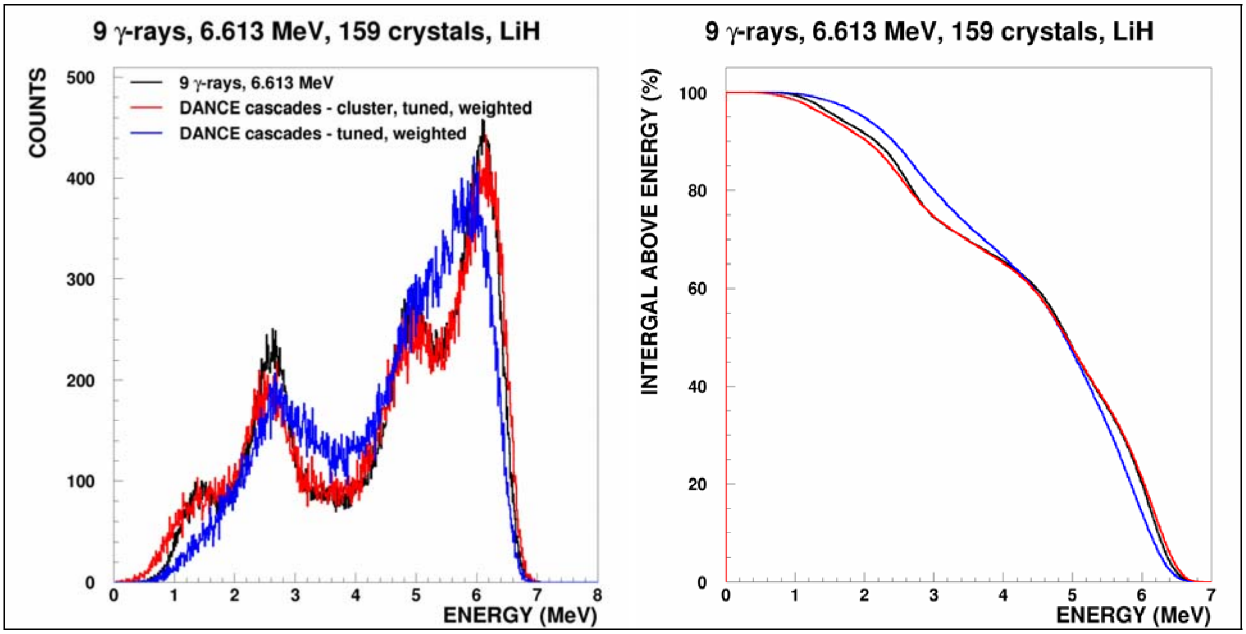

Figure 19: Left: Simulated response of the DANCE array with 159 crystals and low detector threshold to 9 γ-rays with energies of 2x 0.1, 2x 0.2, 2x 0.3, 0.4, 1.4 and 3.613 MeV (the sum is 6.613 keV) gained from the preceding simulation. No LiH moderator was included. Right: Percentage of counts above a given threshold energy for the spectra on the left. The curves are normalized to the number of emitted γ-cascades, which means, the value at E = 0 MeV reflects the total efficiency of the array.

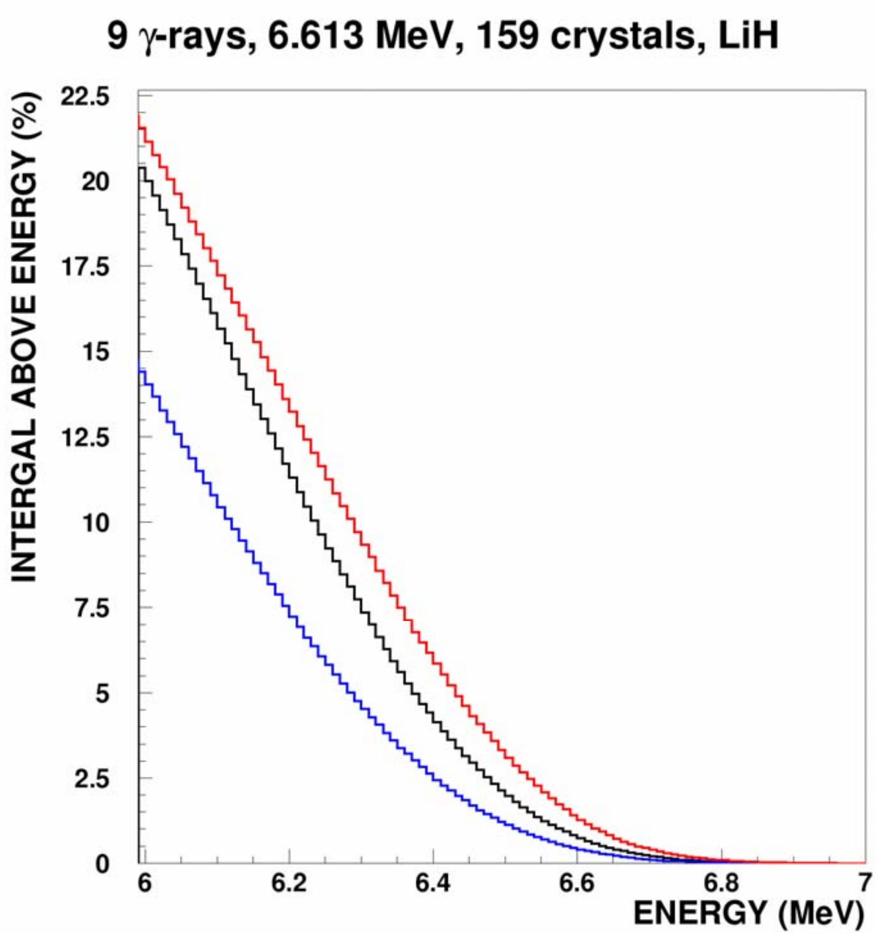

Figure 20: Percentage of counts above a given threshold energy: Zoom into the region between 4 and 7 MeV of the right part of Figure 19.

Table 6: The first 3 columns contain the same data as the right part of Figure 19. The last column contains the relative difference (a-b)/(a+b)*2 in % of the results of the two different simulations (columns 2 and 3).

Energy (MeV)	Efficiency (%) Primary	Efficiency (%) Cluster	Rel. Difference (%)
0	100.0	100.0	**0.0**
0.2	100.0	100.0	**0.0**
0.4	100.0	99.9	**0.1**
0.6	100.0	99.8	**0.2**
0.8	99.9	99.3	**0.6**
1	99.4	98.4	**1.0**
1.2	98.3	97.1	**1.3**
1.4	96.7	95.6	**1.2**
1.6	95.0	94.0	**1.0**
1.8	93.3	92.2	**1.2**
2	91.6	90.3	**1.4**
2.2	89.5	87.9	**1.8**
2.4	86.4	84.7	**2.0**
2.6	82.1	81.0	**1.4**
2.8	77.7	77.4	**0.4**
3	74.5	74.6	**-0.2**
3.2	72.4	72.5	**-0.1**
3.4	70.6	70.6	**0.1**
3.6	68.9	68.8	**0.1**
3.8	67.2	67.0	**0.4**
4	65.5	65.1	**0.6**
4.2	63.5	63.0	**0.9**
4.4	61.1	60.3	**1.3**
4.6	57.8	56.8	**1.7**
4.8	53.2	52.5	**1.4**
5	47.8	47.7	**0.2**
5.2	42.6	42.8	**-0.5**
5.4	38.0	38.3	**-0.8**
5.6	33.2	33.6	**-1.2**
5.8	27.5	28.0	**-1.9**
6	20.0	21.2	**-5.7**
6.2	11.3	13.2	**-15.7**
6.4	4.1	5.9	**-34.5**
6.6	0.7	1.3	**-52.9**
6.8	0.0	0.0	**0.0**
7	0.0	0.0	**0.0**
7.2	0.0	0.0	**0.0**
7.4	0.0	0.0	**0.0**
7.6	0.0	0.0	**0.0**
7.8	0.0	0.0	**0.0**
8	0.0	0.0	**0.0**

5 Conclusions

A method of determining the cascade detection efficiency of the DANCE detector based on the experimental data taken during the specific experiment has been developed and tested (Table 7).

Table 7: The table contains a summary of the highlighted results in Table 1 .. Table 6. The detector was simulated with 159 crystals and low single detector thresholds.

Setup	Energy (MeV)	Rel. Difference (%)
Uhl, no LiH	6	**-2.9**
	6.2	**-3.7**
	6.4	**-6.5**
1 γ-ray, no LiH	6	**1.8**
	6.2	**2.9**
	6.4	**4.5**
9 γ-rays, no LiH	6	**-0.2**
	6.2	**-4.3**
	6.4	**-12.9**
Uhl, LiH	6	**-3.8**
	6.2	**-5.8**
	6.4	**-9.7**
1 γ-ray, LiH	6	**1.8**
	6.2	**3.4**
	6.4	**6.1**
9 γ-rays, LiH	6	**-5.7**
	6.2	**-15.7**
	6.4	**-34.5**

The method is based on information gained from a small energy window around the Q-value of the reaction under investigation. It has been shown that, independent from the primary cascades, the detection efficiency of the reconstructed and primary cascades do not differ by not more than 3%, if a energy interval of at least 600 keV can be analyzed This means, if there are is no other way of determining the cascade efficiency, this method is able to provide this information to better than 3% accuracy.

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